MARS TUMBLEWEED: A NEW WAY TO EXPLORE MARS

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ABSTRACT

Mars Tumbleweed is a novel design for a wind powered surface rover to collect atmospheric and geological data at multiple locations on Mars. The project was broken down into four major phases: Preliminary Design, Downselect, Primary Design, and Manufacturing. During Primary Design, four Mars Tumbleweed designs were considered and analyzed. In the Downselect Phase, the Box Kite concept was chosen. The Primary Design Phase developed it into a Tumbleweed Earth Demonstrator vehicle called TED. This vehicle will demonstrate the capability to operate on the surface of a planet, and to collect and transmit science data. During the Manufacturing Phase, the TED was built with an instrumentation package in the core. The instrumentation included a GPS receiver, for use on earth, accelerometers, pressure transducers, temperature sensors, and a video camera. The data collected are transmitted to a remote ground station.

1. INTRODUCTION

The planet Mars is currently the focus of a great deal of attention and enthusiasm. Tantalizing clues hint that the planet was once warmer and wetter than it is today, and that it may have once supported microbial life. It has a wide range of geologic land forms, including very large scale volcanic structures, enormous impact basins, polar ice deposits, and features that appear to have been produced by the action of surface or subsurface water. Much of what is known about the surface environment of Mars comes from the three successful landers that have visited the Red Planet, Viking I and Viking II in 1976, and Mars Pathfinder in 1997.

Many questions remained to be answered about the origin, history, and current state of Mars: How much water did Mars once have, and how much remains? Has Mars experienced outflows of liquid water in the geologically recent past? How does the atmosphere of Mars affect the geology, and vice versa? Data that can help answer some of these questions may need to be obtained at many locations globally, but it also may need to be obtained by direct means rather than remote sensors. These are contradictory requirements for even the most sophisticated of robotic spacecraft.

A novel solution to the problem of global, in-situ data collection is to design a robot with the capabilities of a rover, but without much of the complexity, and with the range on the order of that of a balloon, but without the severe buoyancy and materials limitations. This type of robot would be powered by the wind, able to travel long distances over very rough terrain, and require very little power to operate. The concept is known as the *Mars Tumbleweed* [1]. Large surface areas of Mars could be covered using multiple Mars Tumbleweed vehicles.

The Mars Tumbleweed Design Project is a collaboration between the NASA Langley Research Center's Spacecraft and Sensors Branch (SSB) the North Carolina State University Aerospace Engineering Space Senior Design Class.

A Mars Tumbleweed has never been placed on Mars, so even the most basic elements of the design are unknown and must be derived from a combination of analysis, testing, and intuition. Therefore this project was subdivided into four main sections: Preliminary Design phase, Downselect phase, Primary Design phase, and Manufacture phase. An Operations Testing phase was also included to verify the concepts.

The project was a two-semester "design and build" project. During the first semester, the basic concepts were investigated and analyzed, and a Tumbleweed vehicle was designed. During the second semester, a scaled proof-of-concept vehicle was built and operated on Earth. The final vehicle design tested data collection and communication capabilities. Lessons learned from the design, manufacture, and demonstration of the proof-of-concept vehicle were provided to NASA [2] for further study of the concept. NASA Langley's SSB also did a collaborative study [3].

Also, as part of an educational outreach program, a group of sixth grade students at Carnage Middle School, a math, science, and technology magnet school in Raleigh, NC, participated in various aspects of the design process [4].

2. PRELIMINARY DESIGN

Four preliminary designs were developed using a combination of theoretical analysis and research into drag-producing structures. The design concepts, shown in Fig. 1, are known as Dandelion, Box-kite, Tumblecup, and Wedges. They were modeled in Unigraphics (UG) and then used to create four scaled physical models that were used during the Downselect phase for wind tunnel testing. For good wind power, a high-drag configuration is needed.

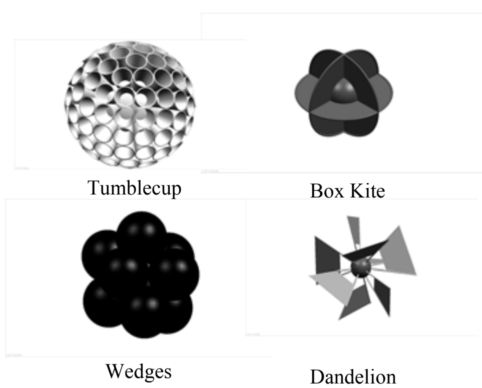

Fig. 1 The design concepts

The Dandelion consists of an inner core with several long spokes protruding outward, on which sails are attached.

The Box-kite structure is adapted from a NASA Langley Spacecraft and Sensors Branch (SSB) tumbleweed concept [3]. This structure consists of the core and three mutually orthogonal discs.

The Tumblecup design has also been adapted from a NASA SSB idea for the tumbleweed concept. The cups increase the surface area of the vehicle, increasing skin friction drag and provide many stagnation points, much like dozens of small parachutes covering the vehicle.

The Wedges design consists of several large lobes connected to a central core. The Wedges design relies on increased skin friction as a means to increase drag, as the lobes simply increase the surface area of the vehicle over that of a sphere.

Before models could be built of the four Tumbleweed concepts, some basic designs were first made using drag approximations. It was reasoned that the best tumbleweed design is required to use the wind as a means of motion (translational and rotational) as efficiently as possible. Therefore there are two issues. The first is to determine how much drag the Tumbleweed vehicle can produce in a particular flow condition. The second is to determine how efficiently the Tumbleweed vehicle is able to convert drag into translational motion through rolling. To simplify the initial design process, the issue of rolling was separated from the issue of drag production.

Finding ways of getting drag information on each design without actually constructing all the possible variants of the four basic models led to the use of computer based tools. These tools allow particular parameters of each concept to be varied for the four models, so that within each particular concept the best basic configuration can be chosen to go on to the next step of actually building scale models for the Downselect phase.

Information about the Martian atmospheric properties collected from the Mars Pathfinder windsock experiment was obtained from [5]. From Viking I surface wind data, it was determined that, on average, gusts to 7 m/s would be frequent during northern fall, and to 15 m/s during the winter. From this information, as well as from the diameter of the Mars Tumbleweed vehicle determined by NASA LaRC SSB of 6m (based on previous rolling-dynamics analysis), the Reynolds number of a Tumbleweed in 7-15 m/s flows on Mars would be, roughly, in the range 50,000-110,000.

Several assumptions were made to help model the analysis of the drag forces: similar flow to that on Mars, inviscid flow over sphere when calculating stream velocity, viscous flow when calculating drag coefficient for the core, viscous flow when calculating drag coefficient for cylindrical spokes, viscous flow when calculating drag coefficient for sails. The amount of drag produced by small objects like Dandelion spokes is negligible if there are larger drag-producing objects present. An infinite cylinder can approximate a cylindrical cross section, and, finally, the velocity at the center point of the sail is far enough from the core to be approximated as free stream velocity.

3. DOWNSELECT

In order to objectively select the best of the four Tumbleweed vehicle concepts for the Primary Design phase, some Figures of Merit (FOM) had to be developed so that each Tumbleweed could be assigned a numerical score. Three FOM were used: amount of drag, number of parts, and total vehicle mass. Each FOM had an equal weighing factor to help downselect to one particular design. Picking the FOM was a difficult task, since not all vehicle design parameters can be known until a more detailed design analysis can be made. This is noticeably apparent in the lack of a rolling ability FOM, given the importance on Tumbleweed's ability to roll as a measure of its ability to travel and gather science data effectively. It was determined that rolling dynamic analysis would be done during the Primary Design phase, and that whichever Tumbleweed concept was chosen during the Downselect process could be modified to enable it to roll more efficiently.

Drag

Aerodynamic drag is source of the Tumbleweed's ability to move across the surface, so it is a very important parameter. The North Carolina State University (NCSU) subsonic wind tunnel was used to obtain drag information on the four Mars Tumbleweed vehicle concepts. In order to get an estimate of the drag that a Tumbleweed vehicle would experience on the surface of Mars, the Reynolds number of the flow inside the subsonic wind tunnel must be matched to the Reynolds number of flow on the surface of Mars, which was previously found to be roughly 50,000-110,000. The Mars Tumbleweed vehicle models, range in diameter from roughly 20-23 cm, therefore under standard atmospheric conditions, the subsonic wind tunnel must be run at between 3.8-8.3 m/s (12.5-27.3 ft/s). It was decided to increase this range somewhat to see how the drag changed as a function of Reynolds number for higher values of Re. Since this represents the near lower limit of the capability of the NCSU subsonic wind tunnel, in order to ensure that the drag data that is collected corresponds to real drag at the tested values of Re, a smooth sphere was tested as a baseline along with the four Tumbleweed models.

The current force balance rig available in the subsonic wind tunnel has a minimum load of approximately 6.5 N. From Hoerner [6], a sphere in the Reynolds number regime of 50,000-110,000 has a drag coefficient C_D=0.47. Since the drag experienced by the sphere would be less than 0.5 N, which would be the lower limit on drag force for all four models, a custom load cell was developed and fabricated. The custom load cell designed used an optical strain gauge that can measure accurately with a maximum error in strain of 1%.

All four models performed much better than the sphere, indicating that a sphere is the least desirable shape for extracting energy (drag) from a flow. Also from [6], a flat plate perpendicular to the flow in the Reynolds number regime that was tested has a C_d=1.17, and is probably the upper limit to what any design could hope to achieve. The Box-kite had the highest average drag coefficient of 1.06, and it is also the concept that is most similar to a flat plate as far as the flow is concerned.

Lastly, the drag coefficients are higher at the lower Reynolds number values, but level off as Re increases. Future analysis will have to be done to determine how other aerodynamic properties, such as lift coefficient and rolling moment, will behave in the same range of Reynolds numbers used for the drag.

Data collected from the wind tunnel experiment was used as the source of information on aerodynamic drag FOM. Points were awarded on a scale from 0 to 1, with $C_{D,sphere}$ being 0, and $C_{D,box\ kite}$ being 1 (due to the fact the box kite had the highest drag coefficient). The box kite had the greatest drag coefficient by a significant margin, receiving almost four points greater than the other three designs.

Parts

The number of parts FOM serves two purposes. First, the number of parts is a direct measurement of how complex a design is from a manufacturing perspective. For this reason, two numbers were used: the total number of major parts and the number of unique parts. It indirectly is also a measure of how easily a particular vehicle may be able to compact into a small size for deployment purposes. Major parts are calculated based on the actual total number of parts and the number of unique parts. The values were calculated by taking the reciprocal of the number of respective parts. Both values were averaged with equal weight and scaled from 0 to 1. The box kite and wedges designs both had the highest ratio.

Mass

For simplicity, it was assumed that the thickness of all materials and average density of all materials was identical. Therefore the surface area of each concept was calculated. The surface area was divided by the radius squared in order for the numbers to be non-dimensional. The dandelion being the least massive of the 4, received all 10 points.

Name and score	*Drag*	*Parts*	*Mass*
Tumble cups *16.67*	6.70	8.78	1.19
Box Kite *23.54*	10.00	10.00	3.54
Balloons *19.27*	6.23	10.00	3.03
Dandelion *23.36*	6.63	6.72	10.00

Table 1. Figure of Merit Chart

The FOM chart with each of the Tumbleweed concept scores is shown in Table 1. Using these scores, the Box-kite concept was chosen as the best concept from the information available to the NCSU Space Senior Design Team during the Downselect Phase. This is the design used for the Tumbleweed Earth Demonstrator (TED).

4. PRIMARY DESIGN

During the Primary Design phase, two separate designs were considered, a Mars Tumbleweed flight vehicle, and the Tumbleweed Earth Demonstrator. This was done to separate the requirements for an actual 6m diameter Tumbleweed that would fly to Mars from the requirements for the NCSU Space Senior Design Team's 2m diameter demonstration vehicle, TED, that was built during the Spring Semester Manufacturing Phase. Unless otherwise stated, all detailed design work refers to TED.

The simple Box-kite model that was chosen during the Downselect Phase was modified based on rolling dynamic considerations. The original Box-kite design has large open areas that hinder the rolling ability of the Tumbleweed. The modified Box-kite is shown in Fig. 2.

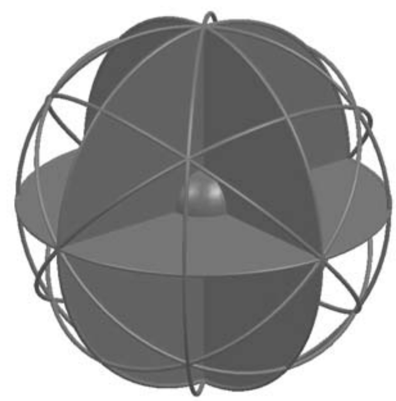

Fig. 2 The modified Box-kite model

It contains several new structures that will dramatically improve the rolling ability of the vehicle, without drastically altering its drag properties. The current design relies on composite structural tube elements surrounding a hollow core containing instrumentation, power, and communication subsystems. Each of the outer tubes on the actual Mars Tumbleweed would be deflated for transportation to Mars, then inflated during deployment with chemicals to rigidize them before operations begin. Since the tubes are rigidized, the gas would not be required for continued inflation.

Fig. 3 Rolling tests

A series of rolling tests were performed to assess the rolling capabilities of TED. See Fig. 3. These experiments were designed to take into account factors that the preliminary analysis could not, yielding a more accurate picture of the actual wind speeds required. A 30 cm model of TED was constructed. A cable was attached to the center of the model and the end of the cable was attached to a cup that was filled with metal pellets with known masses. It was determined that below a scaled rock size of 0.75 m, the geometry of the Tumbleweed model was such that it behaved the same as if there were no rocks at all, because of the open spaces in the model.

Based on rolling dynamics testing and wind tunnel testing data, the actual Mars Tumbleweed will require wind speeds on the order of 17 m/s on Mars in order to move across rough terrain. Particularly windy regions on Mars may be investigated as landing sites, and Tumbleweed may operate as a fixed facility during most of the day, only traveling briefly from one location to another when the winds are strong enough.

The total diameter of TED, 2m, was chosen as a compromise between building a vehicle large enough to be a good analogue to a full size Mars Tumbleweed, see Fig. 4, but small enough to be manageable by the NCSU Space Senior Design Team and also due to the higher atmospheric density on Earth.

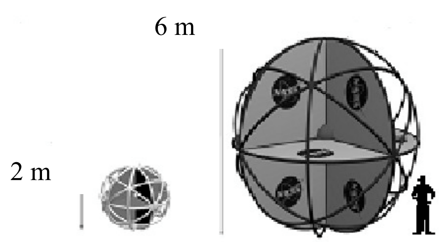

Fig. 4 TED compared with Mars Tumbleweed

ANSYS, a Finite Element Modeling software package, was used to do preliminary structural analysis to determine the sizing of the rings required to make TED structurally sound for testing on Earth.

Mars Tumbleweed would have 12 cm inflatable-rigidizable tubes, three 38.1 μm layers of Carbon/Kevlar hybrid and exterior Kapton layers. A fully inflatable-rigidizable TED would be beyond the scope of this project. Therefore as a compromise it was decided to manufacture TED as it would be in its fully deployed and rigidized state. It was built out of 7.62 cm pre-rigidized tubes with two 25.4 μm layers of Carbon/Kevlar hybrid and a painted outer layer. All parts were fabricated separately and assembled into the final shape of TED

Instruments and Subsystem Considerations

The purpose of the instruments on TED was not only to acquire useful science data to demonstrate the effectiveness of Tumbleweed in accomplishing a science mission, but to also test the vehicle dynamic characteristics and capabilities to determine more information as to how a Tumbleweed vehicle operates in the field.

Several instruments were chosen for TED, for both testing and data acquisition. One such instrument was a GPS receiver/transmitter package. The GPS instrument was used as a way of collecting position and velocity history of the Tumbleweed vehicle in field tests. It also provided real-time tracking capabilities of the actual finished model for field testing. Research was done on existing commercially available GPS receivers such as the Garmin 17-N and the Holux GM-210.

The mission goals included an imager to be part of the Tumbleweed payload. The instrument that was chosen was a miniature camera that could take video while the rover is rolling. This was considered as an instrument on the Earth demonstrator as a way of determining the capabilities and limitations of an imager on such a dynamic platform as the Tumbleweed vehicle.

The core was optimized to operate in an Earth environment for demonstration purposes on TED. For example, there is no thermal subsystem and the redundancy of systems required for a space flight project has not been added. Originally, the core was partially modified to operate solely in a Martian environment, but this was quickly changed due to the level of complexity, and is not necessary for the purpose of demonstration testing on Earth.

The power subsystem basically consists of six 9-V rechargeable batteries. This power pack provides energy to all systems.

The communication subsystem is the telemetry transmitter and receiver. These operate at 433 MHz. Only the transmitter will be aboard the tumbleweed. The range of the transmitter is approximately five miles with the addition of a

Yagi antenna to the receiver. The receiver is connected to a laptop which will store all data.

The instrumentation subsystem consists of a pressure sensor, a temperature sensor, accelerometers, and a CCD camera. The pressure and temperature sensors are built into the R-DAS flight computer along with a uniaxial accelerometer. Another biaxial accelerometer was added to provide data in the x, y, and z directions.

The data handling subsystem is the R-DAS flight computer. This will regulate all functions of the other subsystems.

To determine if the flight computer and its components would be able to fit into the proposed core size, which is 0.2 meters, they were modeled in Unigraphics. The layout that was used is that of a modified hollow sphere. The components were each placed into the sphere based on their volume dimensions, as shown in Fig. 5.

The core was built by Fineline Prototyping, Inc. in Raleigh, NC. It was made using stereolithography, where a UV-tuned laser that precisely traces cross-sections of the model cures a resin. Once it was proven that the instruments would all fit into the design, they were rearranged to optimize the center of mass characteristics. he only component that is not included in the current design is the placement of the camera. The best camera placement will have to be determined once a complete vehicle design is finalized and the capabilities of the camera are known more precisely.

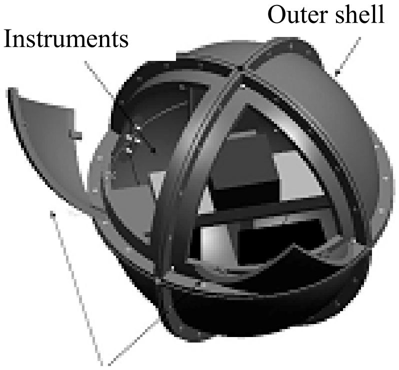

Fig. 5 Detail of the TED core, showing outer shell and access hatches

The core was designed not only to protect the instruments, but also to provide a support structure for the sails and outer rings. The rings attach to the core by means of tension ropes. Each of the eight core segments is bolted through the sails, and the tensile loads from the sails are transmitted to the core through the sail holders.

5. MANUFACTURING PHASE

The first step in the manufacturing process was to determine how the various vehicle components would be manufactured and assembled. TED had to be easily manufactured and tested in one semester using materials and supplies that were readily available. It also had to be easy to disassemble and transport, as field testing would require that TED fit inside a readily available vehicle, and a 2 m diameter spherical object was too large. Also, because of the limitation of metric materials and supplies in the U.S., all manufacturing was done in English units. Therefore the original 2 m diameter TED was changed to 2 yd. (36 in.) and the tube diameters were changed from 8 cm to 3 in.

The tube molds

The molds were constructed out of fiberglass and epoxy resin around the plug and parting planes. A special solution called Poly vinyl alcohol, or PVA, was used as a release agent for getting the molds apart from the parting planes and each other.

The tubes

To create a tube a carbon fiber/Kevlar hybrid was used that was lightweight (approximately 2oz/yd), cut into 2.5 in. strips of about 40 in. long and epoxy resin applied to it. The inflation rubber tubing was wrapped in plastic wrap to ensure that the epoxy did not cure to the rubber. The impregnated strips were then wrapped around the rubber tubing at an angle in which each section is covered by two or more layers of laminated composite material, as seen in Fig. 6.

Fig. 6 Epoxy-impregnated fibers were wrapped around rubber tubing, which was kept under pressure inside mold until epoxy cure

TED structural assembly
First, as seen in Fig. 7, a block of wood 1.5 in. high was anchored to the center of the floor using duct tape, and a hole was drilled where the chosen center of TED would start. This was done so that TED would not move during construction. A solid piece of metal with holes drilled out for markers to represent the inner and outer radius was attached to the center point so that it could swivel, and guide circles were drawn on the floor to guide the location of the tubes.

The sail material was made out of ¾ oz. rip-stop nylon bought from Bainbridge sails. Grommets and hooks were used to suspend the sails from the outer structure. The hooks were placed on the tube structure a constant distance away from each other in an alternating pattern.

Fig. 7 First part of quadrant pieces were placed

6. OPERATIONS TESTING

Due to time and weather constraints, only preliminary operations testing has been performed at this time. The wind conditions were not favorable on days when TED was in the field. However, all the instrumentation has been tested in the core outside of TED. A sample output from the onboard GPS unit is shown in Fig. 8.

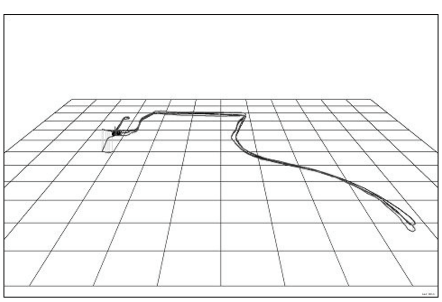

Fig. 8 Sample output from TED onboard GPS unit (grid size: 100m x 100m)

The GPS unit maintained a lock on satellites despite multiple orientations, indicating that it can be used for future dynamic studies of TED in the field. Sample output from the onboard 3-axis impact accelerometers and outputs from the pressure and temperature sensors were also obtained. Although all the sensors are quite precise, there appears to be a great deal of noise in their output making them less accurate than would be ideal.

7. FUTURE WORK AND CONCLUDING REMARKS

One test that unfortunately was unable to succeed during the NCSU Mars Tumbleweed design project was a more detailed wind tunnel experiment. A more advanced wind-tunnel model and test rig was constructed, but because of a series of mechanical and equipment failures was not able to provide any useful data before the end of the semester. The advanced rig was motorized, allowing the model to be rotated during testing. Tests were to be performed while the model was rotating, and also with the model stationary but at various "angles-of-attack." Also, a large and very rough surface was constructed to test the model against a simulated surface boundary layer.

Future plans for the Tumbleweed Earth Demonstrator vehicle, Fig. 9, are to continue field operations testing, including incorporation of the onboard camera.

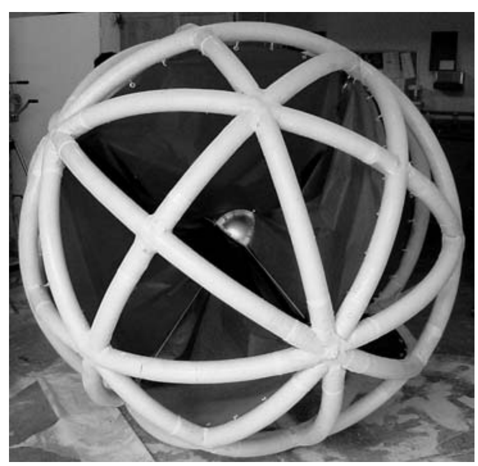

Fig. 9 Tumbleweed Earth Demonstrator

A possible future proposed project would be for students to transport TED to the Utah Mars Desert Research Station (MDRS), which is run by the Mars Society. Finding a local field testing site with constant, high winds would also be useful. It would also be of value to build an inflatable tube and test the concept of inflation and rigidization for an actual Mars tumbleweed. Other tests, such as those in [7], will also be pursued.

A great deal of knowledge was gained during the course of the two-semester design project, but more work still needs to be done. The NCSU Mars Tumbleweed team has identified some key properties of Tumbleweed that should be investigated more closely in the future. First of all, based on wind tunnel data and our best estimates on the mass of a full-scale Mars Tumbleweed, the dynamic behavior of a fully-rigidized Tumbleweed is somewhat more limited than was originally planned. The Martian atmosphere is quite thin, providing very little dynamic pressure to power a wind-propelled rover like Mars Tumbleweed. Since the Tumbleweed Earth Demonstrator design is rigid, rather than inflatable, its mass is rather high, even with a heavy reliance on lightweight composite materials. Mission planners will probably want to select particularly windy locations on Mars to land Tumbleweed, which may include many landing sites that are off-limits to traditional landers. Mars Tumbleweed is a unique and very promising concept that is worth investigating further.

8. ACKNOWLEDGEMENTS

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